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RESEARCH

Effects of Deep Cryogenic Treatment on Friction and Wear of EN24 Steel Against Alumina Under Dry and Lubrication Conditions

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A B S T R A C T

As-received (AsRec) EN24 steel was treated with conventional heat treatment (ConHeatTreat) without tempering followed by deep cryogenic treatment (DeepCryoTreat) as a supplemental treatment to study its tribological behaviour against alumina without or with mineral oil (MO) under different normal loads of 1 N and 5 N. The ConHeatTreat of the AsRec-EN24 obtained an 218.5% improvement in its hardness as the supplemental DeepCryoTreat of the ConHeatTreat-EN24 resulted in a 11.7% further improvement in its hardness. As a result, the ConHeatTreat-EN24 had the 67.5% and 56.3% lower wear volumes for 1 N and 5 N under dry condition and the 53.6% lower wear volume for 5 N under MO lubrication condition compared to those of the AsRec-EN24, respectively. The DeepCryoTreat-EN24 had the 11.5% and 39.7% lower wear volumes for 1 N and 5 N under dry condition and the unmeasurable wear volume for 5 N under MO lubrication condition compared to those of the ConHeatTreat-EN24, respectively. It could be concluded that the supplemental DeepCryoTreat further improved the hardness and thereby the abrasive wear resistance of the ConHeatTreat-EN24 under both dry and lubrication conditions.

1. INTRODUCTION

EN24 steel is widely used for mechanical components such as tools, axles, gears, shafts, studs, bolts, screws, rods, rollers, pins, etc. because of its high tensile strength, hardness, elastic modulus, and wear resistance [1-3]. However, moving or rotating components made of EN24 steel can generate their apparent surface wear during prolonged rubbing contact with counter materials under heavy loads, which can lead to a significant failure risk of the components in long-run [4-6]. The cost associated with wear of mechanical components is huge and wear consequentially becomes an important issue to industry [7,8]. Therefore, various treatments that can improve the hardness and wear resistance of EN24 steel are always interestingly sought in order to promote the quality, efficiency, reliability, durability, performance, and service life of mechanical components for industrial applications.

In aerospace, automotive, agricultural and marine industries, DeepCryoTreat has been widely used as a supplemental and permanent treatment after ConHeatTreat to improve the hardness and wear resistance of steels because DeepCryoTreat eliminates retained austenite and precipitates fine secondary carbides [8-11]. Since transforming retained austenite in steel into martensite reduces its working lifespan via brittle failure such as micro-cracking, elimination of retained austenite by DeepCryoTreat can lessen its brittle failure [12,13]. Akhbarizadeh et al. [14] reported that DeepCryoTreat-D6 tool steel had the better tribological performance than quenched and tempered steel. Dixit et al. [15] explored the effects of DeepCryoTreat on the tribological performance of D5 tool steel with a significant improvement in its wear resistance. Khun et al. [8] revealed that DeepCryoTreat significantly improved the wear resistance of ConHeatTreat-D3 tool steel. Bobyr et al. [16] investigated the influence of the duration of DeepCryoTreat on the micro-hardness and wear resistance of 38CrNi3MoV steel and found its highest wear resistance with 1 hr holding time. Kara et al. [17] found an improvement in the wear resistance of AISI D2 tool steel with DeepCryoTreat. It is clear that DeepCryoTreat can be used as an effective supplemental treatment to further improve the wear resistance of EN24 steel. Comprehensive understanding of how DeepCryoTreat affects the structural, mechanical and tribological properties of EN24 steel is important for its successful use in mechanical components.

It is necessary to use lubricating oils for the lower wear and longer service life of steel since lubricating oils can effectively reduce the friction and wear of rubbing surfaces [18,19]. Therefore, comprehensive understanding of the tribological behaviour of DeepCryoTreat-EN24 steel under lubrication condition is also important to be successfully applied in mechanical components. However, the wear behaviour of DeepCryoTreat-EN24 steel under dry and lubrication conditions has not been widely reported in the literature yet.

In this study, the wear behaviour of the AsRec-EN24, ConHeatTreat-EN24, and DeepCryoTreat-EN24 under dry and MO lubrication conditions was comparatively investigated at room temperature (RT~22-24°C). Their microstructures and hardness were studied using X-ray diffractometry (XRD), optical microscopy (OM), and Vickers micro-hardness test, respectively. For tribo-tests, alumina balls were used as counter balls because counter alumina balls with the much higher wear resistance compared to that of steel balls could perfectly generate the wear and evaluate the wear resistance of the EN24 steel without the interference of the wear of counter steel balls.

2. EXPERIMENTAL DETAILS

2.1 Sample preparation

Commercially available EN24 steel (0.36-0.44 C%, 0.45-0.7 Mn%, 0.1-0.35 Si%, 1.0-1.4 Cr%, 1.3-1.7 Ni%, 0.2-0.35 Mo%, 0.03 P%, 0.04 S%, and Fe balance) rods of 12 mm in diameter were machined into discs with 10 mm in diameter and 5 mm in thickness. The AsRec-EN24 was treated with ConHeatTreat to 850 °C followed by soaking for 15 min and quenching in an oil with 30 °C (Table 1), and not further tempered. For the DeepCryoTreat, the ConHeatTreat-EN24 without tempering was cooled from RT to -196 °C in 6 hr using liquid nitrogen in A.C.I. CP-200vi cryogenic processor of Applied Cryogenics Inc., Massachusetts, USA followed by holding at -196 °C for 24 hr and heating back to RT in 6 hr (Table 1).

Table 1. Detailed treatments of EN24 steel.

Sample ID	Hardening Temperature	Soaking Period	Quench Medium	DeepCryoTreat Cycle
AsRec-EN24	Not Applicable	Not Applicable	Not Applicable	Not Applicable
ConHeatTreat-EN24	850 °C	15 min	Oil at 30 °C	Not Applicable
DeepHeatTreat-EN24	850 °C	15 min	Oil at 30 °C	DeepCryoTreat Cycle

2.2 Characterization

Zeiss Axioskop 2 OM with JVC color video camera was used to observe the microstructures of the AsRec-EN24, ConHeatTreat-EN24, and DeepCryoTreat-EN24 and the wear scars of the worn alumina (Al_2O_3) balls. The mirror-like surfaces of the polished AsRec-EN24, ConHeatTreat-EN24, and DeepCryoTreat-EN24 using a chemical mechanical polishing method were etched with 4 wt.% nital to observe their detailed microstructures. Their microstructures were evaluated using Philips MPD 1880 XRD with Cu-Kα radiation powered with 40 kV and 40 mA.

Vicker micro-hardness test was applied to measure the micro-hardness values of the AsRec-EN24, ConHeatTreat-EN24, and DeepCryoTreat-EN24. Their average hardness values were taken from ten random indentations on each sample under an applied normal load of 200 g (1.96 N).

CSM ball on disc micro-tribometer was used to generate the wear and measure the friction of the AsRec-EN24, ConHeatTreat-EN24, and DeepCryoTreat-EN24 against 6 mm alumina balls in a circular path of 0.8 mm in radius for 40,000 laps at a sliding speed of 4 cm/s under different normal loads of 1 N and 5 N without or with laboratory grade ACROS MO. Three tribo-tests for each type were carried out to average the tribological results. Taylscan 150 surface profilometry with a contact mode 4 µm diamond stylus was used to scan their 3D wear tracks from which the wear widths and depths were measured to calculate the wear volumes. JEOL-JSM-5800 scanning electron microscopy (SEM) equipped with EDX system was used to observe their wear morphologies and detect the chemical elements of their untested and tested areas.

3. RESULTS AND DISCUSSION

The detailed microstructures of the AsRec-EN24, ConHeatTreat-EN24, and DeepCryoTreat-EN24 are presented in Figure 1. The microstructure of the AsRec-EN24 has large and elongated primary carbides, and smaller and nearly spherical secondary carbides as revealed with white regions in Figure 1a [4,20,21]. The ConHeatTreat of the AsRec-EN24 apparently reduces the size of the carbides in its microstructure (Figure 1b) as the DeepCryoTreat of the ConHeatTreat-EN24 gives rise to a further reduction in the size of the carbides in its microstructure (Figure 1c) [8,20,21]. Therefore, the most uniform carbide size distribution is found in the microstructure of the DeepCryoTreat-EN24 (Figure 1c).

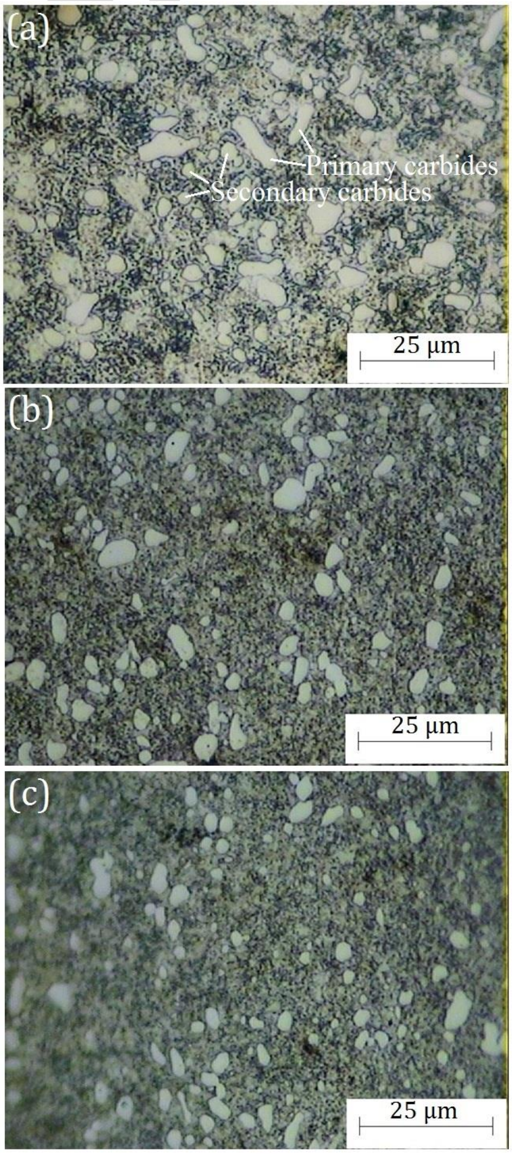

Fig. 1. Microstructures of (a) AsRec-EN24, (b) ConHeatTreat-EN24, and (c) DeepCryoTreat-EN24.

Figure 2 presents the XRD patterns of the AsRec-EN24, ConHeatTreat-EN24, and DeepCryoTreat-EN24 in which the untempered martensite peaks are found. The XRD patterns of the AsRec-EN24 and DeepCryoTreat-EN24 have the strongest and weakest retained austenite peaks, respectively [8,11,22].

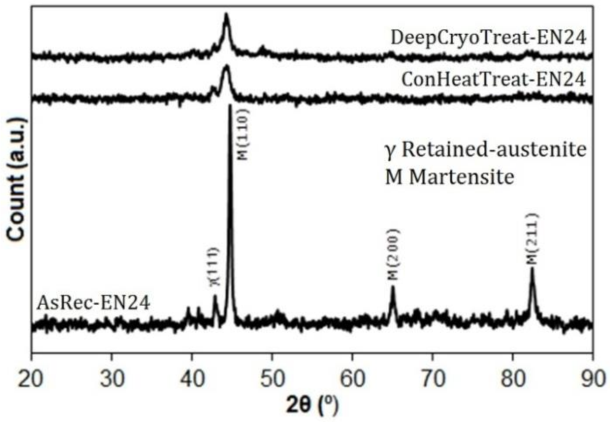

Fig. 2. XRD patterns of AsRec-EN24, ConHeatTreat-EN24, and DeepCryoTreat-EN24.

Figure 3 presents the micro-hardness values of the AsRec-EN24, ConHeatTreat-EN24, and DeepCryoTreat-EN24. The hardness of the AsRec-EN24 is 324 Hv. The ConHeatTreat-EN24 has the 218.5% higher hardness of 1032 Hv, indicating that the ConHeatTreat significantly improves the hardness of the AsRec-EN24 [8,22,23]. The DeepCryoTreat of the ConHeatTreat-EN24 results in a 11.7% further increment in the hardness so that the hardness of the DeepCryoTreat-EN24 is 1153 Hv [8,22,23].

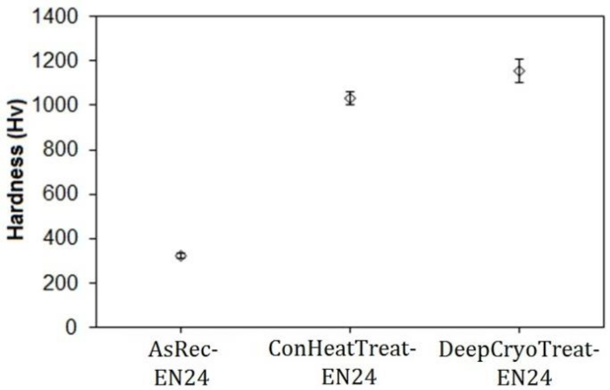

Fig. 3. Micro-hardness values of AsRec-EN24, ConHeatTreat-EN24, and DeepCryoTreat-EN24.

Figure 4 shows the wear volumes of the AsRec-EN24, ConHeatTreat-EN24, and DeepCryoTreat-EN24 tested dry under the normal loads of 1 N and 5 N. The wear volumes of the AsRec-EN24 are 48.3×10^{-4} mm^3 for 1 N and 334.2×10^{-4} mm^3 for 5 N. The ConHeatTreat-EN24 has the lower wear volumes of 15.7×10^{-4} mm^3 (67.5% lower) for 1 N and 146.2×10^{-4} mm^3 (56.3% lower) for 5 N while the DeepCryoTreat-EN24 has the further lower wear volumes of 13.9×10^{-4} mm^3 (11.5% further lower) for 1 N and 88.2×10^{-4} mm^3 (39.7% further lower) for 5 N. The wear results clearly reveal that the ConHeatTreat significantly improves the hardness and thereby the wear resistance of the AsRec-EN24 as the DeepCryoTreat of the ConHeatTreat-EN24 results in a further improvement in its wear resistance associated with its further promoted hardness [8,22,24]. However, the repeated dry sliding of the alumina balls under the larger normal load generates the larger wear volumes of all the AsRec-EN24, ConHeatTreat-EN24, and DeepCryoTreat-EN24 [25,26].

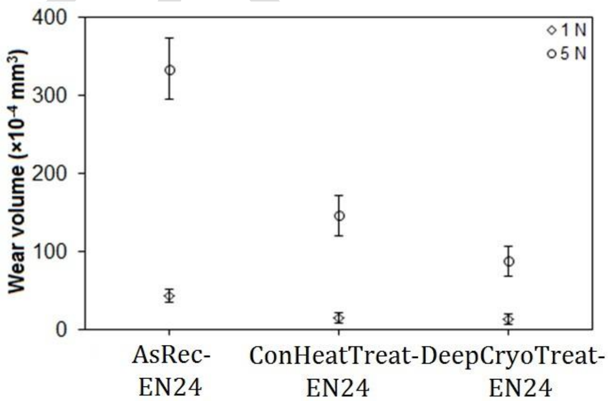

Fig. 4. Wear volumes of AsRes-EN24, ConHeatTreat-EN24, and DeepCryoTreat-EN24 tested without MO under normal loads of 1 N and 5 N.

The AsRec-EN24 and ConHeatTreat-EN24 lubricated with the MO under 5 N have the much lower wear volumes of $0.97\pm0.45\times10^{-4}$ mm^3 (99.7% lower) and $0.45\pm0.06\times10^{-4}$ mm^3 (99.7% lower) compared to their ones tested dry under the same normal load, respectively. Under the lubrication condition, the ConHeatTreat-EN24 has the 53.6% lower wear volume than the AsRec-EN24 as the wear volume of the DeepCryoTreat-EN24 is not measurable. It indicates that the DeepCryoTreat-EN24 has the highest wear resistance among the EN24 samples under the MO lubrication condition. Nevertheless, the presence of the MO during the sliding greatly lowers the wear volumes of all the AsRec-EN24, ConHeatTreat-EN24, and DeepCryoTreat-EN24. The MO can be therefore considered as an effective lubricant for the EN24.

Figure 5 shows the friction coefficients of the AsRec-EN24, ConHeatTreat-EN24, and DeepCryoTreat-EN24 tested without or with the MO under different normal loads. The friction coefficients of the AsRec-EN24 tested dry under the normal loads of 1 N and 5 N are 0.86 and 0.81, respectively. The ConHeatTreat of the AsRec-EN24 gives rise to the lower friction coefficients of 0.84 for 1 N and 0.78 for 5 N. The DeepCryoTreat of the ConHeatTreat-EN24 results in the further lower friction coefficients of 0.81 for 1 N and 0.72 for 5 N. Since a larger contact area between two rubbing surfaces gives rise to higher friction via a larger number of contact junctions between them, it is supposed that the decreased friction of the EN24 with ConHeatTreat and DeepCryoTreat results from its decreased contact area with its counter alumina ball during the dry sliding via its decreased wear [8,27-29].

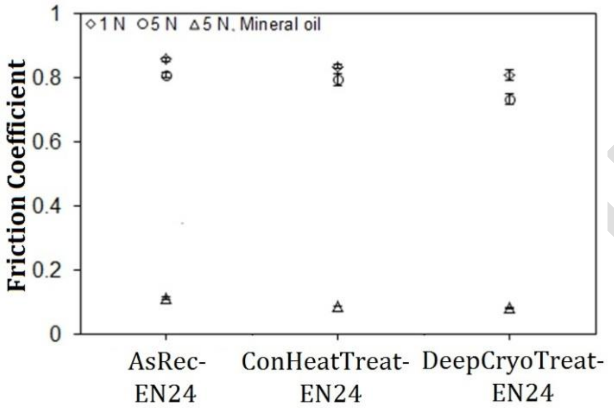

Fig. 5. Friction coefficients of AsRec-EN24, ConHeatTreat-EN24, and DeepCryoTreat-EN24 tested without or with MO under normal loads of 1 N and 5 N.

The AsRec-EN24, ConHeatTreat-EN24, and DeepCryoTreat-EN24 tested dry exhibit their lower friction under the higher normal load as found in Figure 5. As an effective interfacial shear strength between two rubbing surfaces in contact generates high friction, roughening of their surfaces via their wear reduces the interfacial shear strength by lessening a real contact area between them [8,30-33]. In addition, a release of wear debris into an interface between two rubbing surfaces also reduces the interfacial shear strength because released wear debris serve as spacers to prevent a direct contact between them and freely roll or slide under a lateral force [8,30-33]. It is clear that the increased wear of the AsRec-EN24, ConHeatTreat-EN24, and DeepCryoTreat-EN24 with increased normal load decreases their friction by increasing the roughening of their rubbing surfaces and the amount of released wear debris. The friction coefficients of the AsRec-EN24, ConHeatTreat-EN24, and DeepCryoTreat-EN24 lubricated with the MO under 5 N are 0.11, 0.09 and 0.08, respectively. It indicates that the lower wear of the EN24 results in its lower friction via its smaller contact area with its counter alumina ball even under the MO lubrication condition. The AsRec-EN24, ConHeatTreat-EN24, and DeepCryoTreat-EN24 have the much lower friction under the MO lubrication condition, confirming that the MO is effective for lubricating the EN24.

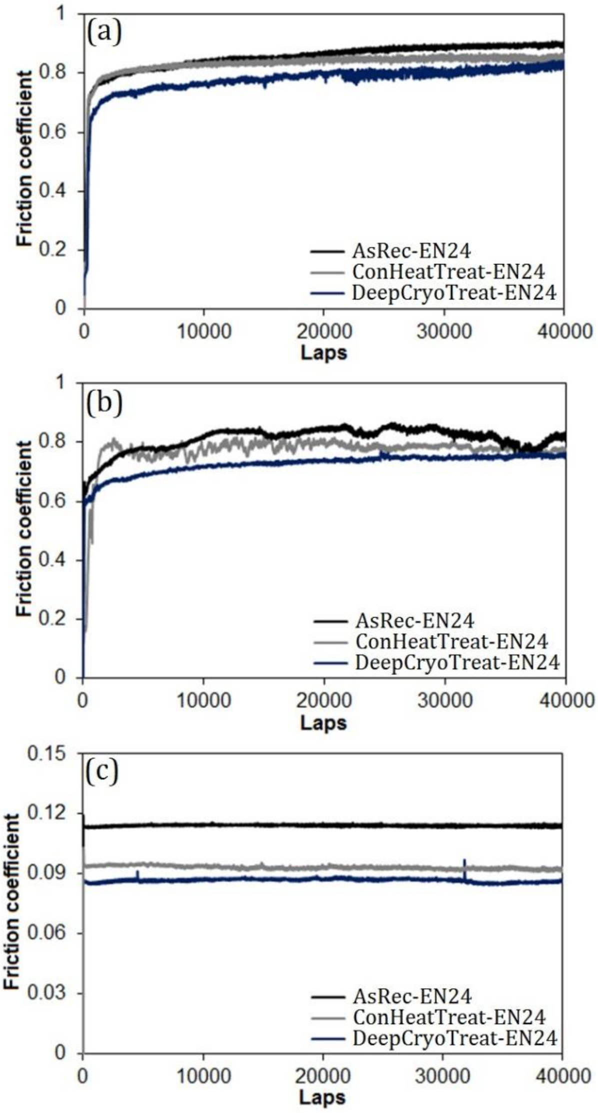

Fig. 6. Friction coefficients of AsRec-EN24, ConHeatTreat-EN24, and DeepCryoTreat-EN24 as a function of the number of laps, tested (a) without MO under a normal load of 1 N , (b) without MO under a normal load of 5 N, and (c) with MO under a normal load of 5 N.

Figures 6a and b illustrate the friction coefficients of the AsRec-EN24, ConHeatTreat-EN24, and DeepCryoTreat-EN24, tested dry under 1 N and 5 N, respectively, with respect to the number of laps. Under 1 N (Figure 6a), the stable friction of the AsRec-EN24, ConHeatTreat-EN24, and DeepCryoTreat-EN24 during the entire sliding is found as a result of their steady wear processes [8,30,34]. Under the higher normal load of 5 N (Figure 6b), the AsRec-EN24 and ConHeatTreat-EN24 exhibit their unstable friction while the friction of the DeepCryoTreat-EN24 is still stable throughout the wear test. It suggests that the DeepCryoTreat-EN24 has the better tribological behaviour even under the higher normal load than the AsRec-EN24 and ConHeatTreat-EN24.

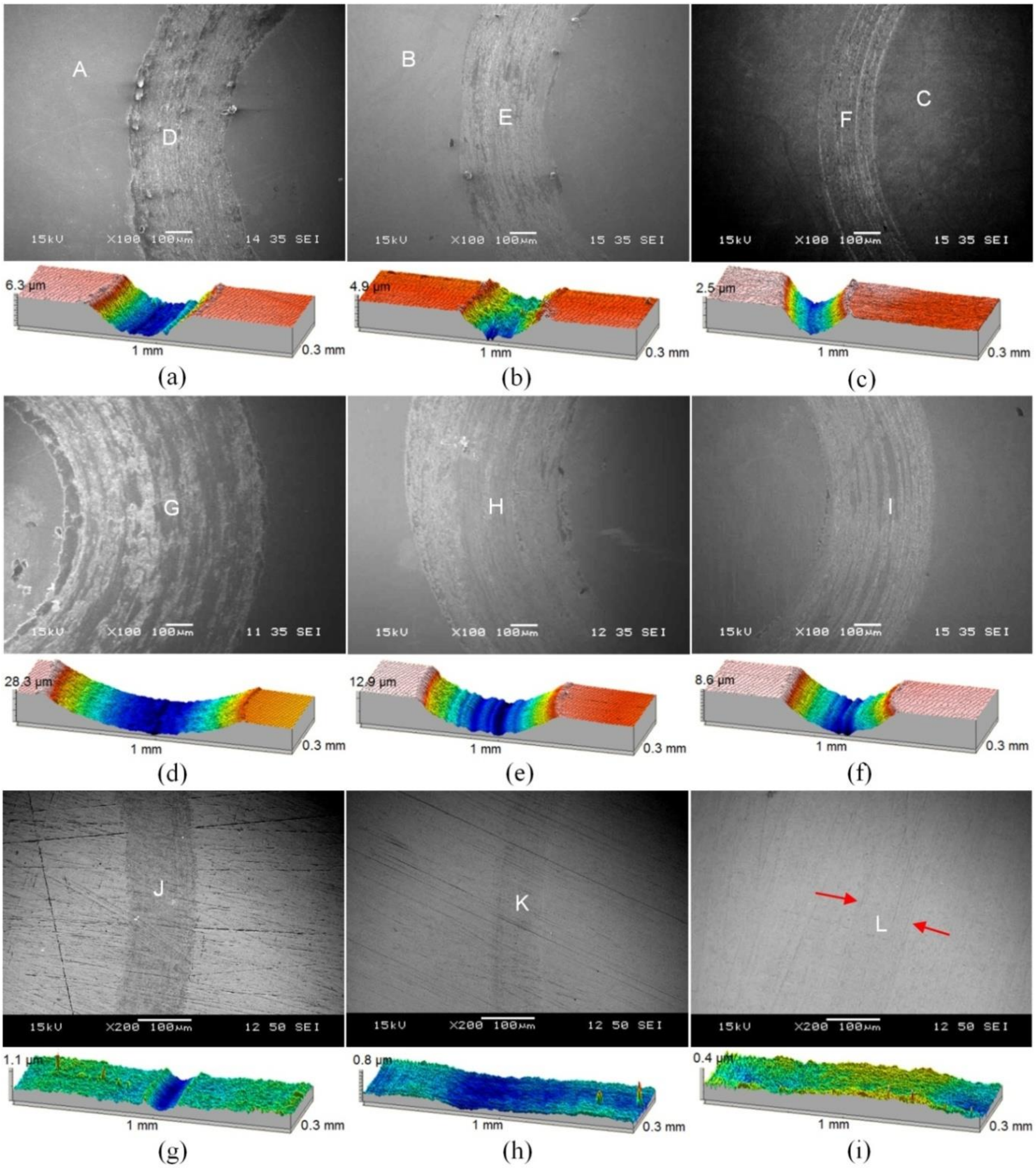

Fig. 7. Wear morphologies and topographies of (a, d and g) AsRec-EN24, (b, e and h) ConHeatTreat-EN24, and (c, f and i) DeepCryoTreat-EN24 tested (a, b, c, d, e, and f) without and (g, h and i) with MO under normal loads of (a, b and c) 1 and (d, e, f, g, h and i) 5 N.

Under 1 N (Figure 6a), the friction coefficients of the AsRec-EN24, ConHeatTreat-EN24, and DeepCryoTreat-EN24 steadily increase with increased laps via a continuous increase in their wear during the prolonged sliding. Such frictional behaviour is not found under 5 N (Figure 6b), especially for the AsRec-EN24 and ConHeatTreat-EN24 due to their pronounced wear under the higher normal load [25,26]. Under both normal loads (Figures 6a and b), the AsRec-EN24 and DeepCryoTreat-EN24 tested dry consistently have the highest and lowest trends of friction coefficient versus lap, respectively.

Figure 6c shows the friction coefficients of the AsRec-EN24, ConHeatTreat-EN24, and DeepCryoTreat-EN24, tested with the MO under 5 N, with respect to the number of laps. They all have the much more stable and much lower friction coefficients for all the laps (Figure 6c) compared to their ones tested dry (Figure 6b) [35]. The AsRec-EN24 and DeepCryoTreat-EN24 still have the highest and lowest trends of friction coefficient versus laps, respectively, because a difference in their wear results in their different frictional behaviour even with the MO.

Figures 7a-f show the wear morphologies and topographies of the AsRec-EN24, ConHeatTreat-EN24, and DeepCryoTreat-EN24 tested dry under 1 N and 5 N. Under both 1 N and 5 N, the AsRec-EN24 (Figures 7a and d) and DeepCryoTreat-EN24 (Figures 7c and f) have the largest and smallest wear tracks, confirming their lowest and highest wear resistance, respectively. It is consistently found that the AsRec-EN24, ConHeatTreat-EN24, and DeepCryoTreat-EN24 have apparently larger wear tracks under the higher normal load of 5 N (Figures 7d-f).

In the tests with the MO under 5 N, the AsRec-EN24 has a measurable wear track on its surface (Figure 7g) while the wear track of the ConHeatTreat-EN24 is less apparent and smaller as found in Figure 7h. However, the wear track of the DeepCryoTreat-EN24 is hardly seen and not measurable (Figure 7i). It indicates that the AsRec-EN24 and DeepCryoTreat-EN24 have the lowest and highest wear resistance, respectively, even under the MO lubrication condition. The presence of the MO during the repeated sliding apparently lowers the wear of the EN24 with different treatments via the lubricating effect of the MO [35]. Therefore, all the lubricated AsRec-EN24, ConHeatTreat-EN24, and DeepCryoTreat-EN24 have the much smaller wear tracks (Figures 7g-i) compared to their ones tested dry (Figures. 7d-f) under 5 N.

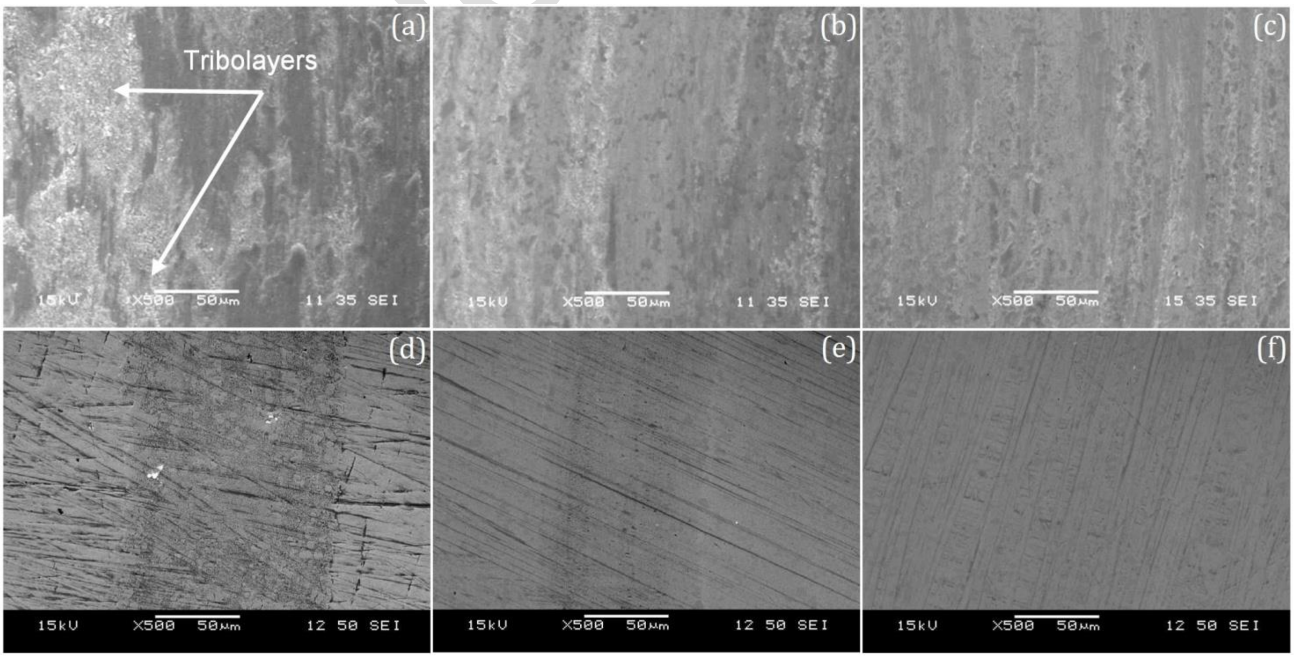

Fig. 8. Wear morphologies of (a and d) AsRec-EN24, (b and e) ConHeatTreat-EN24, and (c and f) DeepCryoTreat-EN24, tested (a, b and c) without and (d, e and f) with MO under a normal load of 5 N, observed at higher magnification.

The highest wear of the AsRec-EN24 tested dry under 5 N (Figure 7d) generates a significant amount of wear debris as the repeated sliding of the alumina ball compacts the wear debris to form tribolayers on its wear track as found in Figure 8a [8,33,36]. Since tribolayers are somewhat harder, the existence of tribolayers on the wear track of the AsRec-EN24 prevents its abrasive wear to some extent [37]. Such tribolayers are less apparently formed on the wear tracks of the ConHeatTreat-EN24 (Figure 8b) and DeepCryoTreat-EN24 (Figure 8c) due to the less generation of wear debris associated with their relatively lower wear (Figures 7e and f).

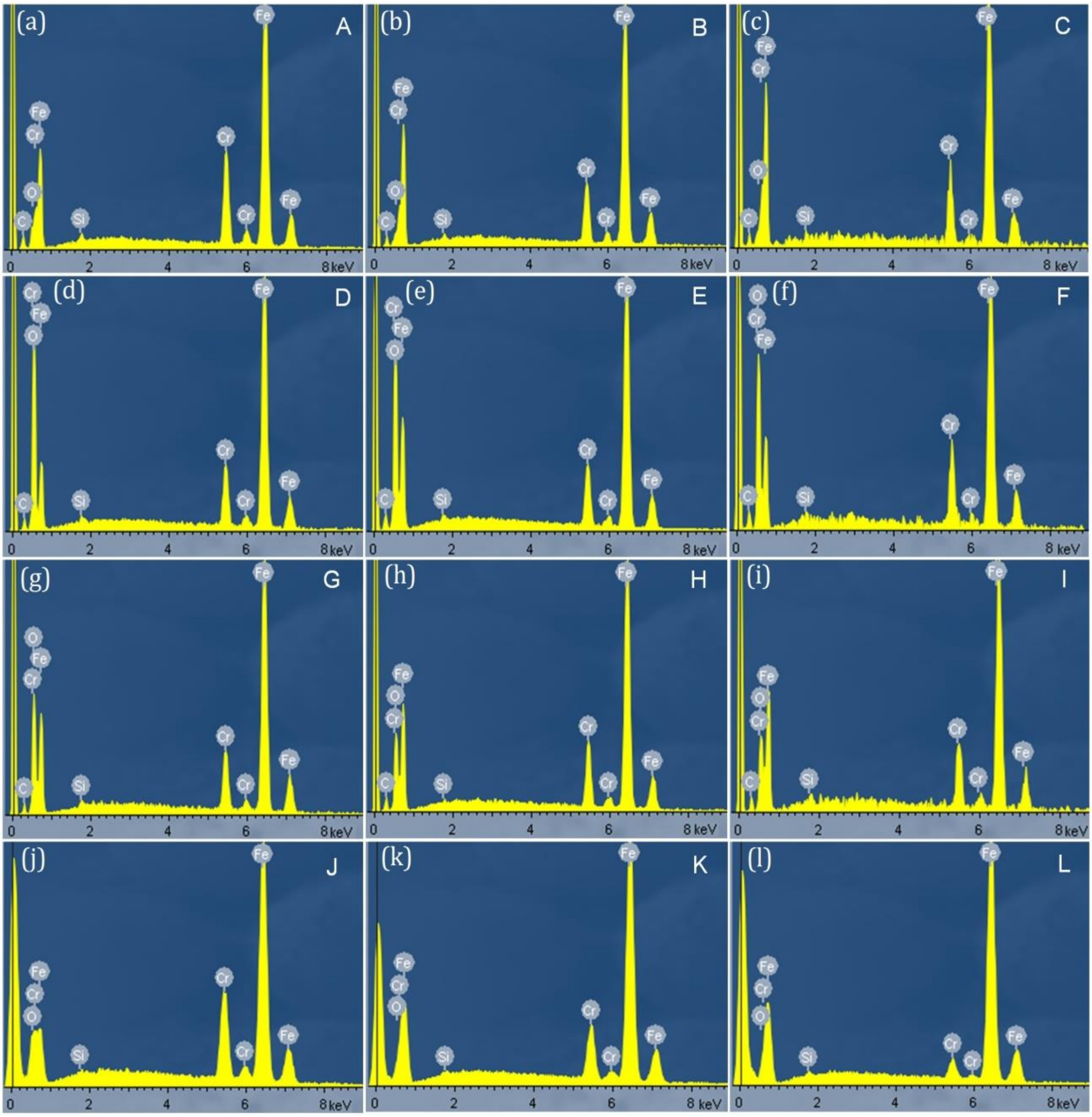

Fig. 9. EDX spectra of (a, d, g and j) AsRec-EN24, (b, e, h and k) ConHeatTreat-EN24, and (c, f, i and l) DeepCryoTreat-EN24, tested (d, e, f, g, h and i) without and (j, k and l) with MO under normal loads of (d, e and f) 1 N and (g, h, i, j, k and l) 5 N, measured at locations (a) A in untested area and (d) D in wear track of Figure 7a, (b) B in untested area and (e) E in wear track of Figure 7b, (c) C in untested area and (f) F in wear track of Figure 7c, (g) G in wear track of Figure 7d, (h) H in wear track of Figure 7e, (i) I in wear track of Figure 7f, (j) J in wear track of Figure 7g, (k) K in wear track of Figure 7h and (l) L in wear track of Figure 7i.

Ploughed furrows (abrasive lines) found on all the wear tracks tested dry (Figures 7a-f and 8a-c) are indicative of the abrasive-wear caused by the repeated dry sliding of the alumina ball [8,30,38]. Since the higher hardness of a solid material can give rise to its lower abrasive wear, the highest hardness of the DeepCryoTreat-EN24 is responsible for its lowest abrasive wear among the EN24 samples used in this study [30,39]. The repeated dry sliding of the alumina ball can cause surface spallation via fatigue wear [40]. However, no observation of surface material removal from subsurface regions as platelets on all the wear tracks indicates that the EN24 is not susceptible to the fatigue wear [40].

Ploughed furrows are not apparently found on the wear tracks of the AsRec-EN24 (Figure 7g and 8d), ConHeatTreat-EN24 (Figure 7h and 8e), and DeepCryoTreat-EN24 (Figure 7i and 8f) lubricated with the MO under 5 N because the presence of the MO between two rubbing surfaces effectively prevents a direct contact between them and lubricates their surfaces to eliminate the abrasive wear [41]. Therefore, the abrasive wear scar on the wear track of the DeepCryoTreat-EN24 (Figure 7i and 8f) is least apparent under the combined effect of its highest abrasive wear resistance and the effective lubrication of the MO.

Figures 9a, b and c illustrate the EDX spectra of the AsRec-EN24**,** ConHeatTreat-EN24, and DeepCryoTreat-EN24, respectively, measured on their untested areas on which C, O, Cr, Si and Fe peaks are mainly detected. The O peak comes from their surface oxygen contaminant [8,30]. The C, Cr, Si and Fe peaks are attributed to their matrixes. Their similar EDX spectra indicate that their chemical compositions do not significantly change with different treatments.

The AsRec-EN24, ConHeatTreat-EN24, and DeepCryoTreat-EN24 tested dry under 1 N and 5 N have similar EDX spectra for their untested areas (Figures 9a-c) and wear tracks (Figures 9d-i). However, the EDX spectra of their wear tracks (Figures 9d-i) have the stronger O peaks, which are attributed to the dry sliding induced oxidation process, compared to those of their untested areas (Figures 9a-c) [8,30,42,43]. In the tests without the MO under 5 N, the AsRec-EN24 has the higher friction than the ConHeatTreat-EN24 and DeepCryoTreat-EN24 as reported in Figure 5, which pronounces the oxidation process by generating higher frictional heat during the dry sliding [8,30,42,43]. As a result, the AsRec-EN24 (Figure 9g) has the stronger O peak on the EDX spectrum of its wear track than the ConHeatTreat-EN24 (Figure 9h) and DeepCryoTreat-EN24 (Figure 9i). The AsRec-EN24, ConHeatTreat-EN24, and DeepCryoTreat-EN24 have the stronger O peaks on all the EDX spectra of their wear tracks under 1 N (Figures 9d-f) than under 5 N (Figures 9g-i), which can be correlated to their higher friction under 1 N (Figure 5).

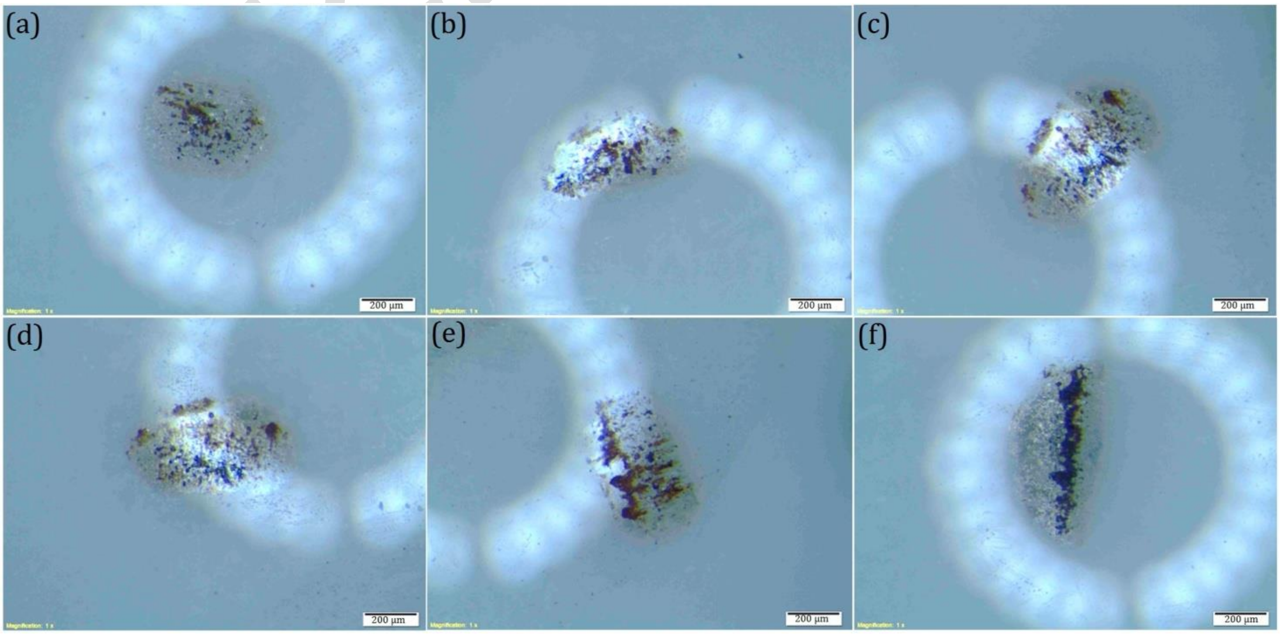

Fig. 10. Wear morphologies of alumina balls rubbed on (a and d) AsRec-EN24, (b and e) ConHeatTreat-EN24, and (c and f) DeepCryoTreat-EN24 without MO under normal loads of (a, b and c) 1 N and (d, e and f) 5 N.

On the EDX spectra measured on the wear tracks of the lubricated AsRec-EN24, ConHeatTreat-EN24, and DeepCryoTreat-EN24 (Figures 9j-l), the C peaks are not apparently discriminated from overlapped surrounding peaks and the O peaks are found weaker compared to those tested dry (Figures 9g-i) because the MO apparently suppresses the frictional heat that is responsible for the oxidation process [44].

Figure 10 shows the wear morphologies of the alumina balls rubbed on the AsRec-EN24, ConHeatTreat-EN24, and DeepCryoTreat-EN24 without the MO under 1 N and 5 N. The abrasive wear scars of the alumina balls are smallest and largest for the AsRec-EN24 and DeepCryoTreat-EN24, respectively, under both normal loads. The abrasive wear scars of the AsRec-EN24, ConHeatTreat-EN24, and DeepCryoTreat-EN24 are larger for 5 N than for 1 N. It can be therefore seen that the highest wear resistance of the DeepCryoTreat-EN24 gives rise to the highest surface wear of its counter alumina ball as the higher normal load of 5 N applied during the dry sliding results in the higher wear of not only the EN24 but also its counter alumina ball.

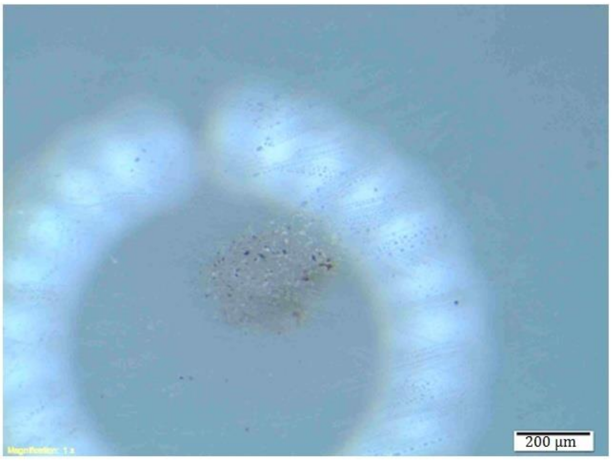

Fig. 11. Wear morphology of alumina ball rubbed on AsRec-EN24 with MO under a normal load of 5 N.

Figure 11 shows the wear morphology of the alumina ball rotated on the AsRec-EN24 with the MO under 5 N. The MO apparently lowers the surface wear of the alumina ball, which is confirmed by the comparison of Figures 10d and 11. The wear scars of the alumina balls rubbed on the ConHeatTreat-EN24 and DeepCryoTreat-EN24 with the MO cannot be clearly identified.

4. CONCLUSION

The friction and wear of the AsRec-EN24, ConHeatTreat-EN24, and DeepCryoTreat-EN24 against the alumina balls without or with the MO under the different normal loads of 1 N and 5 N were investigated together with their microstructures and hardness.

- The DeepCryoTreat-EN24 had the most uniform carbide size distribution in its microstructure among the EN24 samples used in this study.
- The ConHeatTreat-EN24 had the 218.5% higher hardness than the AsRec-EN24 as the hardness of the DeepCryoTreat-EN24 was 11.7% higher than that of the ConHeatTreat-EN24. The DeepCryoTreat-EN24 had the highest hardness among the EN24 samples used in this study.
- The ConHeatTreat-EN24 had the 67.5% and 56.3% lower wear volumes for the normal loads of 1 N and 5 N under the dry condition and the 53.6% lower wear volume for 5 N under the MO lubrication condition compared to those of the AsRec-EN24, respectively. The DeepCryoTreat-EN24 had the 11.5% and 39.7% lower wear volumes for 1 N and 5 N under the dry condition and the unmeasurable wear volume for 5 N under the MO lubrication condition compared to those of the ConHeatTreat-EN24, respectively.
- The ConHeatTreat significantly improved the abrasive wear resistance of the AsRec-EN24 via its improved hardness as the DeepCryoTreat gave rise to the further improved wear resistance of the ConHeatTreat-EN24 by further promoting its hardness. The DeepCryoTreat-EN24 had the highest abrasive wear resistance among the EN24 samples used in this study.
- The presence of the MO during the prolonged sliding effectively reduced the wear of the AsRec-EN24, ConHeatTreat-EN24, and DeepCryoTreat-EN24. The DeepCryoTreat-EN24 had the lowest wear even under the MO lubrication condition.
- It could be concluded that the DeepCryoTreat was a promising supplemental treatment to further improve the hardness and abrasive wear resistance of the ConHeatTreat-EN24.

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